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# Best approximation in Hardy spaces and by polynomials, with norm constraints

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**Abstract:** Two related approximation problems are formulated and solved in Hardy spaces of the disc and annulus. With practical applications in mind, truncated versions of these problems are analysed, where the solutions are chosen to lie in finite-dimensional spaces of polynomials or rational functions, and are expressed in terms of truncated Toeplitz operators. The results are illustrated by numerical examples. The work has applications in systems identification and in inverse problems for PDEs.

**Key-words:** Hardy space, extremal problem, polynomial approximation, rational approximation, Toeplitz operators, truncations.

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**Résumé :** Nous formulons et résolvons des problèmes de meilleure approximation sous contraintes dans les espaces de Hardy du disque unité et de l'anneau. Avec des perspectives algorithmiques et numériques, nous étudions des versions tronquées de ces mêmes problèmes : on en cherche des solutions dans des espaces de polynômes. Ces solutions sont exprimées en termes d'opérateurs de Toeplitz tronqués. Nous illustrons également numériquement certains des résultats obtenus. Les problèmes considérés ont des applications en identification de systèmes et dans la résolution de problèmes inverses pour des équations aux dérivées partielles.

**Mots-clés :** Espaces de Hardy, problème extrémal, approximation polynômiale, approximation rationnelle, opérateurs de Toeplitz, troncatures.

## 1 Introduction

Let  $\mathbb{G} \subset \mathbb{C}$  be equal to either the disk  $\mathbb{D}$  or the annulus  $\mathbb{A}$  (or to any conformally equivalent domain with Dini-smooth boundary [26]) and  $1 < p < \infty$ . Let  $I \subset \partial\mathbb{G}$  with positive Lebesgue measure, such that  $J = \partial\mathbb{G} \setminus I$  also has positive Lebesgue measure.

In the Hardy spaces  $H^p(\mathbb{G})$ , whose definitions are recalled in Section 2, we consider for both cases the following best constrained boundary approximation question.

For a given function  $f \in L^p(I)$  and prescribed numbers  $c \in \mathbb{C}$ ,  $M \geq 0$ , find a solution  $g_c = g(c, f, M; \mathbb{G}, I)$  to

$$\|f - g_{c|_I}\|_{L^p(I)} = \min_g \{\|f - g|_I\|_{L^p(I)}, g \in H^p(\mathbb{G}), \|g|_J - c\|_{L^p(J)} \leq M\}. \quad (1)$$

This is an abstract *bounded extremal problem*, related to those studied in [2, 6, 7, 8, 13, 14, 15, 34] for various configurations. Namely, the simply connected situation where  $\mathbb{G} = \mathbb{D}$  is considered for  $p = 2$  in [2, 6], for  $1 \leq p < \infty$  in [7], and for  $p = \infty$  in [8]. The doubly connected case  $\mathbb{G} = \mathbb{A}$  is handled in [13, 14, 34] for  $p = 2$  and in [15] for  $1 < p < \infty$ .

Numerous applications of this constrained approximation issue have been found in the areas of systems identification, parameter identification and inverse problems for PDEs. In particular, we mention: [9], where bounded extremal problems were applied to band-limited frequency-domain systems identification; [23], where inverse diffusion problems were studied; and [21, 22], where approximation problems on the annulus were applied to boundary inverse problems for 2D elliptic PDEs.

Below, we study some finite order discretization schemes for problem (1) in classes of polynomials and trigonometric polynomials (as model spaces of  $H^p(\mathbb{G})$ , cf. [25, Part B, Ch. 3]). Well-posedness properties will be recalled for  $1 \leq p < \infty$ , and constructive aspects will be developed, together with error estimates and convergence properties, including preliminary numerics in the Hilbertian case  $p = 2$ .

Further, a new and more subtle issue is to allow  $c$  to vary, so that we minimize jointly over  $(g, c) \in H^p(\mathbb{G}) \times \mathbb{C}$ , and this leads us to the next best-approximation issue.

For a given function  $f \in L^p(I)$  and a prescribed  $M \geq 0$ , find a function  $g_* \in H^p(\mathbb{G})$  and a constant  $c_* \in \mathbb{C}$  such that  $\|g_*|_J - c_*\|_{L^p(J)} \leq M$  and

$$\|f - g_*|_I\|_{L^p(I)} = \inf_{(g,c)} \{\|f - g|_I\|_{L^p(I)}, g \in H^p(\mathbb{G}), c \in \mathbb{C}, \|g|_J - c\|_{L^p(J)} \leq M\}. \quad (2)$$

Well-posedness will be established for such problems with  $1 < p < \infty$ , together with a density result of traces on  $I \subset \partial\mathbb{G}$  of  $H^p(\mathbb{G})$  functions. For these issues also, constructive aspects are discussed.

The following comment about geometries is pertinent: in the simply connected situation  $\mathbb{G} = \mathbb{D}$ , with  $I \subset \mathbb{T}$ ,  $J = \mathbb{T} \setminus I$ , the associated Toeplitz operator has no eigenvalues; for  $\mathbb{G} = \mathbb{A}$ , where  $\partial\mathbb{A}$  is made up of two circles, say  $s\mathbb{T}$  ( $0 < s < 1$ ) and  $\mathbb{T}$ , two type of situations may occur, depending on whether  $I$  is equal to one of these circles or not. The second case is strongly related to that of the disk, because the Toeplitz operator again has no eigenvalues,

while the first allows easier computations, because there is a basis of eigenvectors.

We will further study below some discretization properties of the Toeplitz operators involved in the resolution schemes when  $p = 2$ , in situations where  $\mathbb{G} = \mathbb{D}$  and  $I \subset \mathbb{T}$  and where  $\mathbb{G} = \mathbb{A}$  and  $I = \mathbb{T}$ . We provide convergence results and error estimates of the computational algorithms, when the solutions are sought in finite-dimensional spaces of polynomials, and therefore expressed with truncated Toeplitz operators (Toeplitz matrices).

We begin in Section 2 by establishing the necessary notation and definitions. The analysis of Problem (2) is undertaken in Section 3. Then, in Section 4 we turn to truncated versions of Problem (1). In Section 5 an explicit solution is given in the case  $\mathbb{G} = \mathbb{A}$  and  $I = \mathbb{T}$ , and this is illustrated by numerical simulations in Section 6. Finally, some conclusions and perspectives for future work are presented.

## 2 Notation, definitions, basic properties

Let  $\mathbb{G}$  be equal to the unit disk  $\mathbb{D}$  or to the annulus  $\mathbb{A}$ .

For  $1 \leq p < \infty$ , the Hardy spaces  $H^p(\mathbb{G})$  are defined as the collection of functions  $g$  analytic in the domain  $\mathbb{G}$  and bounded there in Hardy norm, see [17, 29]:

$$\|g\|_{H^p} = \sup_{\varrho < r < 1} \left[ \frac{1}{2\pi} \int_0^{2\pi} |g(re^{i\theta})|^p d\theta \right]^{1/p} < \infty,$$

with  $\varrho = 0$  if  $\mathbb{G} = \mathbb{D}$  and  $\varrho = s$  if  $\mathbb{G} = \mathbb{A}$ . We could similarly define the Hardy spaces  $H^p(\mathbb{C} \setminus s\overline{\mathbb{D}})$ , which can be directly seen as the image of  $H^p(\mathbb{D})$  functions under the isomorphism  $g \mapsto zg(s/z)$ . In the same way, the set  $H_0^p(\mathbb{C} \setminus s\overline{\mathbb{D}})$  of functions in  $H^p(\mathbb{C} \setminus s\overline{\mathbb{D}})$  that vanish at  $\infty$ , is the image under the same isomorphism of the subset  $H_0^p(\mathbb{D}) \subset H^p(\mathbb{D})$  of functions that vanish at 0.

The space  $H^p(\mathbb{A})$  is isomorphic to the direct sum of two Hardy spaces of simply connected domains:

$$H^p(\mathbb{A}) = H^p(\mathbb{D}) \oplus H_0^p(\mathbb{C} \setminus s\overline{\mathbb{D}}). \quad (3)$$

Every  $H^p(\mathbb{G})$  function  $g$  admits a non-tangential limit (trace)  $g|_{\partial\mathbb{G}}$  on  $\partial\mathbb{G}$ , which defines the subset  $H^p(\partial\mathbb{G}) \subset L^p(\partial\mathbb{G})$ .

The  $H^p(\partial\mathbb{G})$  coincides with the closure of algebraic, respectively trigonometric, polynomials, for  $\mathbb{G} = \mathbb{D}$ , resp.  $\mathbb{A}$  (the closure in  $L^p(\partial\mathbb{G})$  of the set of all rational functions with no poles in  $\overline{\mathbb{G}}$ ). The two spaces  $H^p(\mathbb{G})$  and  $H^p(\partial\mathbb{G})$  are isometrically isomorphic. We thus identify a function  $g \in H^p(\mathbb{G})$  with its non-tangential limit (trace)  $g|_{\partial\mathbb{G}}$ , see [17, 29], and we have  $\|g\|_{H^p} = \|g|_{\partial\mathbb{G}}\|_{L^p(\partial\mathbb{G})}$ .

When  $p = 2$ , the above Hardy spaces are Hilbert spaces with respect to the  $L^2(\partial\mathbb{G})$  inner product. In this case, the direct sum (3) is orthogonal, and Fourier bases are Hilbert bases. Let  $P_{H^2}$  denote the orthogonal projection from  $L^2(\partial\mathbb{G})$  onto  $H^2(\mathbb{G})$ . For  $\Omega \subset \partial\mathbb{G}$  and  $\varphi \in L^2(\Omega)$  we put for simplicity

$$\frac{1}{2\pi} \int_{\Omega} \varphi = \frac{1}{2\pi} \int_{\varrho e^{i\theta} \in \Omega} \varphi(\varrho e^{i\theta}) d\theta = \frac{1}{2\pi\varrho} \int_{z \in \Omega} \varphi(z) |dz|,$$

with  $\varrho = 1$  if  $\Omega \subset \mathbb{T}$  (or in  $\Omega \cap \mathbb{T}$ ) and  $\varrho = s$  if  $\Omega \subset s\mathbb{T}$  (or in  $\Omega \cap s\mathbb{T}$ ).

In the sequel, for  $f \in L^p(I)$  and  $k \in L^p(J)$ ,  $f \vee k$  will denote the function of  $L^p(\partial\mathbb{G})$  equal to  $f$  on  $I$  and equal to  $k$  on  $J$ . Most of the time,  $f$  or  $k$  will be supposed equal to 0. We use the notation  $\chi_\Omega g$ , where  $\chi_\Omega$  is the characteristic function of  $\Omega$ , when  $g$  is defined on the whole  $\partial\mathbb{G}$ .

### 3 Analysis of Problem (2)

For a given  $M \geq 0$ , we introduce the approximation subsets of  $H^p(\mathbb{G})$ , denoted by  $\mathcal{B}_{M,c}$ ,  $c \in \mathbb{C}$  and  $\mathcal{B}_M$  as follows. For  $c \in \mathbb{C}$ , put

$$\mathcal{B}_{M,c} = \{ g \in H^p(\mathbb{G}), \|g|_J - c\|_{L^p(J)} \leq M \},$$

$$\mathcal{B}_M = \{ g \in H^p(\mathbb{G}), \|g|_J - c\|_{L^p(J)} \leq M \text{ for some } c \in \mathbb{C} \} = \bigcup_{c \in \mathbb{C}} \mathcal{B}_{M,c}.$$

For simplicity, we omit in the above notation the dependence with respect to  $p, \mathbb{G}$  and  $I$ . Observe that for every  $M \geq 0$  and  $c \in \mathbb{C}$ , the constant function  $g \equiv c$  always belongs to  $\mathcal{B}_{M,c}$ .

#### 3.1 Well-posedness

The existence and uniqueness of Problem (2) is given by the following theorem.

**Theorem 1** *Let  $1 < p < \infty$ . For every  $M > 0$  and  $f \in L^p(I)$ , there exist a unique function  $g_* = g_*(f, M; p, \mathbb{G}, I) \in \mathcal{B}_M \subset H^p(\mathbb{G})$  and a constant  $c_* = c_*(f, M; p, \mathbb{G}, I) \in \mathbb{C}$  such that*

$$\|f - g_*|_I\|_{L^p(I)} = \inf_{(g,c)} \{ \|f - g|_I\|_{L^p(I)}, g \in \mathcal{B}_{M,c}, c \in \mathbb{C} \}.$$

*Moreover, if  $f \notin \mathcal{B}_{M|_I}$ , then the solution  $(g_*, c_*)$  is unique and saturates the constraint:  $\|g_*|_J - c_*\|_{L^p(J)} = M$ .*

To prove Theorem 1, we need a preliminary density result.

**Proposition 1** *Let  $1 < p < \infty$ . Whenever  $J = \partial\mathbb{G} \setminus I$  has positive Lebesgue measure, then  $H^p(\mathbb{G})|_I$  is dense in  $L^p(I)$ .*

*Proof:* Whenever  $\mathbb{G} = \mathbb{D}$ , the density of  $H^p(\mathbb{D})|_I$  into  $L^p(I)$  directly follows from Runge's theorem [28, Thm. 13.6], since  $|J| > 0$ , see [7, 8].

When  $\mathbb{G} = \mathbb{A}$ , the density result for  $I = \mathbb{T}$  (or  $I = s\mathbb{T}$ ) is established in [13]. When  $I$  is a subset of only one connected component of  $\partial\mathbb{A}$  ( $I \subsetneq \mathbb{T}$  or  $I \subsetneq s\mathbb{T}$ ), the density is a consequence of the topological additive decomposition of  $H^p(\mathbb{A})$  on Hardy spaces of the related connected components (Property (3) below).

The same conclusion in situations where  $I \cap \mathbb{T} \neq \emptyset$  and  $I \cap s\mathbb{T} \neq \emptyset$  holds true, as follows from classical approximation theorems, because  $I$  is a proper closed subset of  $\partial\mathbb{A}$ . First, we use the density of  $C(I)$  in  $L^p(I)$ . Next, the Hartogs–Rosenthal theorem [20, Chap. II] asserts that every continuous function on  $I$  is the uniform limit of rational functions with poles in the complement of  $I$ , since  $I$  has plane measure zero (this fact may also be obtained from a version of Mergelyan's theorem).



But by Runge's theorem [28, Thm. 13.6] every function analytic on a neighbourhood of  $I$  can be uniformly approximated on  $I$  by rational functions with poles at 0 and  $\infty$  only, that is, elements of  $H^p(\mathbb{A})$  (when  $\mathbb{C} \setminus I$  is connected, as in the two above situations, one can even use polynomials) and the result follows. ■

*Proof of Theorem 1:* Introduce the following operators  $A$  and  $B$ :

$$\begin{aligned} A : H^p(\mathbb{G}) \times \mathbb{C} &\longrightarrow L^p(I) \\ (g, c) &\longmapsto g|_I \end{aligned}$$

$$\begin{aligned} B : H^p(\mathbb{G}) \times \mathbb{C} &\longrightarrow L^p(J) \\ (g, c) &\longmapsto g|_J - c. \end{aligned}$$

In view of [15, Lem. 2.1], the next result holds for  $1 < p < \infty$ . If  $A$  and  $B$  are bounded linear operators with dense ranges, which are also coprime in the sense that there exists  $\delta > 0$  such that for all  $(g, c) \in H^p(\mathbb{G}) \times \mathbb{C}$ ,

$$\|A(g, c)\|_{L^2(I)} + \|B(g, c)\|_{L^p(J)} \geq \delta \|(g, c)\|_{H^p(\mathbb{G}) \times \mathbb{C}}, \quad (4)$$

then, if  $f \notin \mathcal{B}_{M|_I}$ , there exists a unique solution  $(g_*, c_*) \in \mathcal{B}_M \times \mathbb{C}$  to Problem (2), and the conclusions of Theorem 1 regarding uniqueness and constraint saturation hold true.

Let us then prove that the above assumptions are satisfied here. First, observe that  $A$  and  $B$  have dense ranges from Proposition 1. Next, we claim that  $A$  and  $B$  satisfy (4), or equivalently that

$$\|g|_I\|_{L^p(I)} + \|g|_J - c\|_{L^p(J)} \geq \delta(\|g|_J\|_{L^p(\partial\mathbb{G})} + |c|).$$

Assume to the contrary that there exists a sequence  $(g_n, c_n) \in H^p(\mathbb{G}) \times \mathbb{C}$ , such that

$$\|g_n\|_{L^p(\partial\mathbb{G})} + |c_n| = 1, \quad (5)$$

while

$$\|g_n|_I\|_{L^p(I)} + \|g_n|_J - c_n\|_{L^p(J)} \rightarrow 0.$$

Because  $(g_n)$  is bounded in  $H^p(\mathbb{G})$ , we may pass to a subsequence and suppose that it is weakly convergent to a function  $g \in H^p(\mathbb{G})$ ; at the same time we may suppose that  $c_n \rightarrow c$  for some  $c \in \mathbb{C}$ . Now  $g = 0$  on  $I$  and so  $g = 0$  everywhere on  $\partial\mathbb{G}$ , by uniqueness results for  $H^p(\mathbb{G})$  functions on subsets of positive measure of the boundary. Also,  $g = c$  on  $J$ , so  $c = 0$ . Finally, we obtain that  $\|g_n\|_{L^p(\partial\mathbb{G})} \rightarrow 0$  and  $c_n \rightarrow 0$ , which is a contradiction to (5). From [15, Lem. 2.1], these properties give the proof in the above situation.

If  $f \in \mathcal{B}_{M|_I}$ , then the best approximation  $g_* = f$  is still unique, although there may exist a set of complex numbers  $c_*$  such that  $\|f|_J - c_*\|_{L^p(J)} \leq M$  (see Lemma 1). ■

### 3.2 Expression of solutions to Problem (2)

Now, let  $p$  be equal to 2. Let us compute the solution  $(g_*, c_*)$ .

### 3.2.1 General situation, $f \notin \mathcal{B}_{M|I}$

Assuming that  $f \notin \mathcal{B}_{M|I}$ ,  $M > 0$ ; the solution  $(g_*, c_*)$  is then given by the implicit equation [14]:

$$(A^* A - \gamma B^* B)(g_*, c_*) = A^* f, \quad (6)$$

for the unique parameter  $\gamma < 0$  such that  $\|g_{*|J} - c_*\|_{L^2(J)} = M$  and the adjoint operators  $A^*$ ,  $B^*$  of  $A$ ,  $B$  that are given from their definition by:

$$\begin{aligned} A^* : L^2(I) &\longrightarrow H^2(\mathbb{G}) \times \mathbb{C} \\ h &\longmapsto (P_{H^2}(h \vee 0), 0) \\ B^* : L^2(J) &\longrightarrow H^2(\mathbb{G}) \times \mathbb{C} \\ \varphi &\longmapsto (P_{H^2}(0 \vee \varphi), -\frac{1}{2\pi} \int_J \varphi). \end{aligned}$$

Then, for  $(g, c) \in H^2(\mathbb{G}) \times \mathbb{C}$ ,

$$A^* A(g, c) = (P_{H^2} \chi_I g|_I, 0), \text{ and } B^* B(g, c) = (P_{H^2} \chi_J (g|_J - c), -\frac{1}{2\pi} \int_J (g|_J - c)).$$

From equation (6), we get:

$$(P_{H^2} \chi_I g_*, 0) - \gamma \left( P_{H^2} \chi_J (g_{*|J} - c_*), -\frac{1}{2\pi} \int_J (g_{*|J} - c_*) \right) = (P_{H^2}(f \vee 0), 0),$$

whence

$$\begin{cases} \frac{1}{2\pi} \int_J (g_{*|J} - c_*) = 0 \\ P_{H^2} \chi_I g_* - \gamma P_{H^2} \chi_J (g_{*|J} - c_*) = P_{H^2}(f \vee 0), \end{cases} \quad (7)$$

for the unique  $\gamma < 0$  s.t.  $\|g_{*|J} - c_*\|_{L^2(J)} = M$ . In particular, we get that  $c_*$  is equal to the normalized mean value of  $g_*$  on  $J$ :

$$c_* = \frac{1}{|J|} \int_J g_{*|J}. \quad (8)$$

Introduce the Toeplitz operator  $T^J = P_{H^2} \chi_J$  of symbol  $\chi_J$  on  $H^2(\mathbb{G})$ , defined by:

$$\begin{aligned} T^J : H^2(\mathbb{G}) &\longrightarrow H^2(\mathbb{G}) \\ g &\longmapsto P_{H^2}(\chi_J g). \end{aligned} \quad (9)$$

We shall discuss such Toeplitz operators in detail later, but for now we merely mention the easily-verified fact that  $T^J$  is self-adjoint and its spectrum is contained in the interval  $[0, 1]$ . Now the second relation in (7) is thus equivalent to:

$$(Id - (\gamma + 1)T^J)g_* = P_{H^2}(f \vee (-\gamma c_*)), \quad (10)$$

hence, with (8),

$$(Id - (\gamma + 1)T^J)g_* + \frac{\gamma}{|J|} T^J \left( \int_J g_{*|J} \right) = P_{H^2}(f \vee 0).$$

Further, (7) is to the effect that

$$\frac{1}{2\pi} \int_I (f - g_{*|I}) = \frac{1}{2\pi} \int_J (g_{*|J} - c_*) = 0 \quad \text{whence} \quad \int_{\partial\mathbb{G}} (g_* - f \vee c_*) = 0.$$

Whenever  $\mathbb{G} = \mathbb{A}$ ,  $I = \mathbb{T}$  and  $J = s\mathbb{T}$ ,

$$\frac{1}{2\pi} \int_{\mathbb{T}} (f - g_{*|_{\mathbb{T}}}) = \frac{1}{2\pi} \int_{s\mathbb{T}} (g_{*|_{s\mathbb{T}}} - c_*) = 0,$$

and because  $g_* \in H^2(\mathbb{A})$ , see Theorem 3, we have

$$\frac{1}{2\pi} \int_{\mathbb{T}} g_{*|_{\mathbb{T}}} = \frac{1}{2\pi} \int_{s\mathbb{T}} g_{*|_{s\mathbb{T}}}, \quad \text{hence} \quad c_* = \frac{1}{2\pi} \int_{\mathbb{T}} g_{*|_{\mathbb{T}}} = \frac{1}{2\pi} \int_{\mathbb{T}} f.$$

### 3.2.2 Approximation class $\mathcal{B}_M$

We begin with the following lemma.

**Lemma 1** *Let  $M > 0$  and  $f_J \in L^2(J)$ . Then, there exists  $c \in \mathbb{C}$  such that  $\|f_J - c\|_{L^2(J)} \leq M$  if, and only if,*

$$\frac{1}{2\pi|J|} \left| \int_J f_J \right|^2 \geq \|f_J\|_{L^2(J)}^2 - M^2. \quad (11)$$

*Proof:* Let  $c \in \mathbb{C}$ ,  $x = \operatorname{Re} c$  and  $y = \operatorname{Im} c$ . We define the function  $\Phi : \mathbb{R}^2 \rightarrow \mathbb{R}$  as follows

$$\Phi(x, y) = -(x^2 + y^2) \frac{|J|}{2\pi} + 2x \operatorname{Re} \left( \frac{1}{2\pi} \int_J f_J \right) + 2y \operatorname{Im} \left( \frac{1}{2\pi} \int_J f_J \right) + M^2 - \|f_J\|_{L^2(J)}^2.$$

The function  $\Phi$  is twice differentiable and  $D\Phi_{(x,y)} = 0$  if and only if

$$x = x_* = \frac{1}{|J|} \operatorname{Re} \left( \int_J f_J \right) \quad \text{and} \quad y = y_* = \frac{1}{|J|} \operatorname{Im} \left( \int_J f_J \right), \quad \text{whence} \quad c_* = \frac{1}{|J|} \int_J f_J.$$

Since the Hessian matrix of  $\Phi$  is  $-2 \frac{|J|}{2\pi} Id$ , then  $\Phi$  has a global maximum at  $(x_*, y_*)$  and

$$\Phi(x_*, y_*) = \frac{1}{2\pi|J|} \left| \int_J f_J \right|^2 + M^2 - \|f_J\|_{L^2(J)}^2.$$

There exists  $c \in \mathbb{C}$  such that  $\|f_J - c\|_{L^2(J)} \leq M$  if and only if  $\Phi(x_*, y_*) \geq 0$ , which is equivalent to (11).  $\blacksquare$

Recall that  $F \in \mathcal{B}_M$  if and only if  $F \in H^2(\mathbb{G})$  and there exists a constant  $c \in \mathbb{C}$  such that  $\|F|_J - c\|_{L^2(J)} \leq M$ , whence, in view of Lemma 1, if and only if  $F|_J$  satisfies (11).

Note that for  $F \in H^2(\mathbb{G})$ , if  $\int_J F|_J = 0$ , then either  $\|F|_J\|_{L^2(J)} \leq M$ , whence  $f \in \mathcal{B}_{M,0}$ , or  $F \notin \mathcal{B}_M$  (from the proof of Lemma 1).

Assume that  $f \in \mathcal{B}_{M|I}$ , in Problem (2). In this situation, and only in this situation, one can and has to choose  $\gamma = 0$  in equation (10), to the effect that  $g_* \equiv F$ , for the function  $F \in \mathcal{B}_M$  such that  $F|_I = f$ . The fact that  $\gamma$  can be made as small as possible truly characterizes the traces on  $I$  of functions in  $\mathcal{B}_M$ , as was discussed in [7] for  $\mathbb{G} = \mathbb{D}$ .

Though there may exist several values for  $c_*$  (the criterion is now equal to 0), the one given by (8) achieves a minimal value for the constraint on  $J$ . Indeed, the argument used in the proof of Lemma 1 is to the effect that whenever (11) holds, the constraint value  $\|f|_J - c\|_{L^2(J)}$  is minimal for

$$c = c_* = \frac{1}{|J|} \int_J f|_J \text{ for which } \|f|_J - c_*\|_{L^2(J)}^2 = \|f|_J\|_{L^2(J)}^2 - \frac{|J|}{2\pi} |c_*|^2.$$

This constraint on  $J$  however is no longer saturated, in this case.

Note that expressions such as  $\|f|_J - c_*\|_{L^2(J)}^2$  (allowing  $J$  to vary) are closely related to the BMO norm of  $f$ .

### 3.3 Degenerate situation $M = 0$

For  $M = 0$  and  $c \in \mathbb{C}$ ,  $\mathcal{B}_{0,c} = \{g \equiv c \text{ on } \mathbb{G}\} = \{c\}$ , whence  $\mathcal{B}_0 = \mathbb{C}$ . With  $f \in L^2(I)$ , Problem (2) becomes

$$\inf_{(g,c)} \{\|f - g|_I\|_{L^p(I)}, g \in \mathcal{B}_{0,c}, c \in \mathbb{C}\} = \inf_{c \in \mathbb{C}} \|f - c\|_{L^p(I)} = \|f - c_*\|_{L^p(I)},$$

and  $g_* \equiv c_*$ . Using the same argument as in section 3.2.2, the solution for  $p = 2$  is equal to

$$c_* = \frac{1}{|I|} \int_I f.$$

Note that for  $p \neq 2$ , one can establish from [10] or from [15] the implicit relation:

$$\frac{1}{|I|} \int_I |f - c_*|^{p-2} (f - c_*) = 0.$$

Situations where  $f \in \mathcal{B}_0 = \mathbb{C}$  then reduce to  $f \equiv c_f \in \mathbb{C}$ , whence  $g_* \equiv c_* \equiv c_f$ .

## 4 Polynomials approximation: truncated Problem (1)

In this section, we focus on the discretization of Problem (1). With an appropriate choice of  $c$  this leads to a discretization of Problem (2).

### 4.1 Analysis of Problem (1)

We recall that  $\mathbb{G}$  denotes the unit disc  $\mathbb{D}$  or the annulus  $\mathbb{A}$ ,  $I \subset \partial\mathbb{G}$  and  $J = \partial\mathbb{G} \setminus I$  are subsets of  $\partial\mathbb{G}$  such that  $I$  and  $J$  have positive Lebesgue measure.

Such problems of minimization have been settled in [2, 7] in the unit disc and for a more general constraint  $\|g|_J - h\|_{L^p(J)} \leq M$  for a given function  $h \in L^p(J)$  and in [13, 34] for the annulus with  $I \subset \mathbb{T}$ .

Let  $1 < p < \infty$ . Given a function  $f \in L^p(I)$ , a complex number  $c$  and a positive number  $M$ , there exists a solution  $g_c \in H^p(\mathbb{G})$  to Problem (1):

$$\|f - g_c|_I\|_{L^p(I)} = \min_g \{\|f - g|_I\|_{L^p(I)}, g \in \mathcal{B}_{M,c}\}.$$

Moreover, if  $f$ ,  $c$  and  $M$  are such that  $f \notin \mathcal{B}_{M,c|_I}$ , then the solution  $g_c$  is unique and the constraint is saturated:  $\|g_{c|_J} - c\|_{L^p(J)} = M$ .

When  $p = 2$ , if  $f$  does not lie in  $\mathcal{B}_{M,c|_I}$ , then the solution  $g_c$  to Problem (1) is given by the implicit equation

$$(Id - (\gamma + 1)T^J)g_c = P_{H^2}(f \vee (-\gamma c)), \quad (12)$$

with  $\gamma < 0$  such that  $\|g_{c|_J} - c\|_{L^2(J)} = M$  and  $T^J$  the Toeplitz operator with symbol  $\chi_J$  defined by (9).

Observe that  $g_c$  given by (12) above and the solution  $g_*$  to Problem (2) given by (10) admit similar expressions ( $g_* = g_{c_*}$ ).

**Remark 1** *It is well known and easy to verify (see, for example, [11, 27] for more general results) that in the case  $\mathbb{G} = \mathbb{D}$  for any nontrivial  $\Omega \subset \mathbb{T}$  the spectrum of  $T^\Omega$  is  $[0, 1]$  and there is no point spectrum. Note that 0 and 1 are in the continuous spectrum of  $T^\Omega$  ( $T^\Omega$  and  $Id - T^\Omega$  are injective and have a dense range respectively). This follows from uniqueness results for  $H^2(\mathbb{D})$  functions on subsets of positive measure of the boundary, see [1, 17] and the self-adjointness of  $T^\Omega$ .*

*In the case  $\mathbb{G} = \mathbb{A}$ , the spectrum of  $T^\Omega$  is again  $[0, 1]$  whenever either  $\Omega$  or its complement has a non-null intersection with both components of  $\partial\mathbb{A}$  (see [1, 4]), and there is no point spectrum.*

*The only case remaining is when  $\mathbb{G} = \mathbb{A}$  and  $\Omega = \mathbb{T}$ , respectively  $\Omega = s\mathbb{T}$ ; then the spectrum of  $T^\Omega$  consists of  $\{0, 1\}$  and the simple eigenvalues (of finite multiplicity), see [1, 34]:*

$$\left\{ \frac{1}{1 + s^{2k}}, k \in \mathbb{Z} \right\}, \text{ respectively } \left\{ \frac{s^{2k}}{1 + s^{2k}}, k \in \mathbb{Z} \right\},$$

*and  $T^\Omega$  has an orthonormal basis of eigenvectors, namely the functions  $z^k / \sqrt{1 + s^{2k}}$  for  $k \in \mathbb{Z}$ ; note that the eigenvalues lie in  $(0, 1)$  and accumulate only at 0 and 1.*

In view of studying convergence properties and numerical aspects of the truncation of the solution of (1), we suggest a new approach to this problem. It consists in considering the problem for functions in classes of polynomials.

## 4.2 Analysis of truncated Problem (1): well-posedness

Let  $N \in \mathbb{N}$  and  $\mathcal{P}_N$  be the subspace of polynomials or trigonometric polynomials, respectively, of  $H^p(\mathbb{G})$  defined by

$$\mathcal{P}_N = \begin{cases} \text{span} \{z^k, 0 \leq k \leq N\} & \text{if } \mathbb{G} = \mathbb{D}, \\ \text{span} \{z^k, -N \leq k \leq N\} & \text{if } \mathbb{G} = \mathbb{A}. \end{cases}$$

**Remark 2** *If  $\mathbb{G} = \mathbb{D}$ , then*

$$\mathcal{P}_N = K_\Theta = H^p(\mathbb{D}) \cap (\Theta H^p(\mathbb{D}))^\perp = H^p(\mathbb{D}) \cap \Theta H_0^p(\mathbb{C} \setminus \overline{\mathbb{D}}),$$

*the model space associated with the finite Blaschke product  $\Theta(z) = z^{N+1}$  (see [25, Part B, Ch. 3] and Section 7.2 for  $\mathbb{G} = \mathbb{A}$ ,  $p = 2$ ).*

Put  $\mathcal{B}_{M,c,N} = \mathcal{B}_{M,c} \cap \mathcal{P}_N$ . Let  $(BEP_N)$  be the following problem: for  $f \in L^p(I)$ ,  $M > 0$  and  $c \in \mathbb{C}$ , we seek  $g_N \in \mathcal{B}_{M,c,N}$  such that

$$\|f - g_N|_I\|_{L^p(I)} = \min_{p_N} \left\{ \|f - p_N|_I\|_{L^p(I)}, p_N \in \mathcal{B}_{M,c,N} \right\}. \quad (BEP_N)$$

When  $p = 2$ , we solve problem  $(BEP_N)$  by giving an expression of the solution  $g_N$  comparable to the implicit equation (12) satisfied by the solution  $g_c$  of (1). As  $(BEP_N)$  is the discretization of (1), a truncation of the Toeplitz operator will naturally appear. This operator is called a truncated Toeplitz operator and was discussed in [30]. On the Fourier basis, it coincides with a Toeplitz matrix of size  $(N+1) \times (N+1)$  if  $\mathbb{G} = \mathbb{D}$ , or  $(2N+1) \times (2N+1)$  if  $\mathbb{G} = \mathbb{A}$ . It is denoted by  $T_N^\Omega$ , for  $\Omega \subset \partial\mathbb{G}$  and defined by

$$\begin{aligned} T_N^\Omega : \mathcal{P}_N &\longrightarrow \mathcal{P}_N \\ p_N &\longmapsto P_N(\chi_\Omega p_N), \end{aligned}$$

where  $P_N$  is the orthogonal projection from  $L^2(\partial\mathbb{G})$  onto  $\mathcal{P}_N$ . Note that the (point) spectrum of the truncated Toeplitz operator  $T_N^\Omega$  is included into  $(0, 1)$  and the invertibility of  $T_N^\Omega$  and  $Id - T_N^\Omega = T_N^{\mathbb{G} \setminus \Omega}$  is due to the finite dimension of  $\mathcal{P}_N$ .

Well-posedness of Problem  $(BEP_N)$  is then ensured by the next result for  $1 < p < \infty$ . Let  $Q_N$  be the projection from  $L^p(I)$  onto  $\mathcal{P}_N|_I$ .

**Theorem 2** *For every  $f \in L^p(I)$ ,  $c \in \mathbb{C}$  and  $M > 0$ , there exists a unique function  $g_N = g_N(f, M; \mathbb{G}, I) \in \mathcal{P}_N$  such that*

$$\|f - g_N|_I\|_{L^p(I)} = \min_{p_N} \{ \|f - p_N|_I\|_{L^p(I)}, p_N \in \mathcal{B}_{M,c,N} \}.$$

Moreover, if  $Q_N f \notin \mathcal{B}_{M,c,N}|_I$ , then the constraint is saturated:  $\|g_N|_J - c\|_{L^p(J)} = M$ .

*Proof:* Observe that  $\mathcal{B}_{M,c,N}|_I$  is a closed and convex set of  $L^p(I)$ . The existence and uniqueness of  $g_N$  follows from the projection theorem on a closed and convex set (see [10]). Now, suppose that  $Q_N(f) \notin \mathcal{B}_{M,c,N}|_I$  and that  $\|g_N|_J - c\|_{L^p(J)} < M$ . Let  $q_N$  be the element of  $\mathcal{P}_N$  such that  $Q_N(f) = q_N|_I$ . One can find  $\lambda \in (0, 1)$  such that

$$\|\lambda q_N|_J + (1 - \lambda)g_N|_J\|_{L^p(J)} \leq M.$$

Since  $\|f - Q_N(f)\|_{L^p(I)} \leq \|f - g_N|_I\|_{L^p(I)}$ , we have that

$$\|f - \lambda Q_N(f) - (1 - \lambda)g_N|_I\|_{L^p(I)} < \|f - g_N|_I\|_{L^p(I)},$$

which contradicts the minimality of  $g_N$ . ■

### 4.3 Convergence properties of solutions to $(BEP_N)$

In this subsection, we establish convergence properties of the solution  $g_N$  and the error estimate  $\beta_N$  to  $g$  and  $\beta$ , respectively (related to Problem (1)).

**Proposition 2** *Let  $M > 0$ ,  $c \in \mathbb{C}$  and  $f \in L^p(I)$ , such that  $f \notin \mathcal{B}_{M,c|_I}$ , and  $N \in \mathbb{N}$ . Let  $g$  and  $g_N$  respectively denote the associated solutions to (1) and  $(BEP_N)$ . We define  $\beta(M) = \|f - g|_I\|_{L^p(I)}$  and for  $N \in \mathbb{N}$ ,  $\beta_N(M) = \|f - g_N|_I\|_{L^p(I)}$  the approximation errors on  $I$  associated to the constraint  $M$  on  $J$ , such that  $M = \|g|_J - c\|_{L^p(J)} = \|g_N|_J - c\|_{L^p(J)}$ . Then,  $(\beta_N(M))_{N \geq 0}$  converges and decreases to  $\beta(M)$  as  $N$  tends to  $+\infty$  and*

$$\|g - g_N\|_{L^p(\partial\mathbb{G})} \rightarrow 0, \text{ as } N \rightarrow \infty.$$

*Proof:* Assume first that  $c = 0$ . The decay of  $(\beta_N(M))_{N \geq 0}$  with  $N$  and the inequality  $\beta_N(M) \geq \beta(M)$  both follow immediately from the increasing of the class of approximants. Let  $\varepsilon > 0$  and  $g_\varepsilon$  be the solution to (1) associated to  $f$  and such that  $\|g_\varepsilon|_J\|_{L^p(J)} \leq M - \varepsilon$ , whence  $\|g_\varepsilon|_J\|_{L^p(J)} = M - \varepsilon$ , see Section 4.1. Since  $\beta$  depends continuously on  $M$ , as a convex function of  $M > 0$ , it holds that

$$\|f - g_\varepsilon|_I\|_{L^p(I)} = \beta(M - \varepsilon) \leq \beta + \delta_\varepsilon,$$

for some  $\delta_\varepsilon$  which goes to 0 with  $\varepsilon$ . Since  $\bigcup_{N \geq 0} \mathcal{P}_N$  is dense in  $H^p(\mathbb{G})$ , there exists  $g_N^\varepsilon \in \mathcal{P}_N$  such that

$$\|g_\varepsilon - g_N^\varepsilon\|_{L^p(\partial\mathbb{G})} \leq \varepsilon.$$

Hence, we have that  $\|f - g_N^\varepsilon|_I\|_{L^p(I)} \leq \beta(M) + \delta_\varepsilon + \varepsilon$  while  $\|g_N^\varepsilon|_J\|_{L^p(J)} \leq M$ . But necessarily, we have that

$$\beta_N(M) \leq \|f - g_N^\varepsilon|_I\|_{L^p(I)} \leq \beta(M) + \delta_\varepsilon + \varepsilon.$$

Letting  $\varepsilon \rightarrow 0$ , we obtain that  $\beta_N(M) \rightarrow \beta(M)$ , as  $N$  tends to  $+\infty$ , which proves the claim. Now, since  $(g_N)_N$  is bounded in  $L^p(\partial\mathbb{G})$  norm uniformly in  $N$  by  $2\|f\|_{L^p(I)} + M$ , we get that every subsequence of  $(g_N)_{N \in \mathbb{N}}$  converges weakly to some function, say  $h \in H^p(\mathbb{G})$ . This implies that

$$\|f - h|_I\|_{L^p(I)} \leq \liminf \|f - g_N|_I\|_{L^p(I)} = \beta(M)$$

while  $\|h|_J\|_{L^p(J)} \leq M$  from [12, Prop. III.12]. Hence,  $h = g$ , and because this holds for every subsequence, we get that  $(g_N)_{N \in \mathbb{N}}$  weakly converges to  $g$  in  $H^p(\mathbb{G})$ ; in particular, the sequence  $(f \vee 0 - g_N|_I)_{N \in \mathbb{N}}$  weakly converges in  $L^p(I)$  to  $f \vee 0 - g|_I$ . As

$$\|f \vee 0 - g_N\|_{L^p(\partial\mathbb{G})} = \beta_N(M) + \|g_N|_J\|_{L^p(J)},$$

we get that

$$\|f \vee 0 - g_N\|_{L^p(\partial\mathbb{G})} \xrightarrow{N \rightarrow +\infty} \|f \vee 0 - g\|_{L^p(\partial\mathbb{G})} = \beta(M) + \|g|_J\|_{L^p(J)}.$$

Applying [12, Prop. III.30], it follows that

$$\|g - g_N\|_{L^p(\partial\mathbb{G})} \rightarrow 0, \text{ as } N \rightarrow \infty.$$

For  $c \neq 0$ , the proof is similar, working with  $g - c$  and  $g_N - c$ . ■

#### 4.4 Expression of solutions to Problem $(BEP_N)$

In the sequel, we let  $p = 2$ . In this case,  $Q_N : L^2(I) \rightarrow \mathcal{P}_{N|I}$  is an orthogonal projection. Since for  $p_N \in \mathcal{P}_N$ , we have that

$$\|f - p_{N|I}\|_{L^2(I)}^2 = \|Q_N(f) - p_{N|I}\|_{L^2(I)}^2 + \|f - Q_N(f)\|_{L^2(I)}^2,$$

we now consider the Problem  $(BEP_N)$  rewritten as follows

$$\|Q_N(f) - g_{N|I}\|_{L^2(I)} = \min\{\|Q_N(f) - g_{|I}\|_{L^2(I)}, g \in \mathcal{B}_{M,c,N}\}.$$

The next lemma gives an explicit expression of  $Q_N(f)$ , for  $f \in L^2(I)$ .

**Lemma 2** *Let  $f \in L^2(I)$ . Then,*

$$Q_N(f) = (R_I^*)^{-1} P_N(f \vee 0) = R_I (T_N^I)^{-1} P_N(f \vee 0),$$

where  $R_I$  denotes the projection from  $\mathcal{P}_N$  onto  $\mathcal{P}_{N|I}$  (restriction map).

*Proof:* Let  $f \in L^2(I)$ . Then,  $f - Q_N(f)$  is orthogonal to  $\mathcal{P}_{N|I}$  for the inner product on  $L^2(I)$  which is equivalent to

$$\langle f - Q_N(f), R_I(q_N) \rangle_{L^2(I)} = 0, \text{ for all } q_N \in \mathcal{P}_N.$$

Hence, for  $q_N \in \mathcal{P}_N$ ,

$$\begin{aligned} \langle R_I^* Q_N(f), q_N \rangle_{L^2(\partial\mathbb{G})} &= \langle Q_N(f), R_I(q_N) \rangle_{L^2(I)} = \langle f, R_I(q_N) \rangle_{L^2(I)} \\ &= \langle P_N(f \vee 0), q_N \rangle_{L^2(\partial\mathbb{G})}. \end{aligned}$$

It follows that  $Q_N(f) = R_I^{*-1} P_N(f \vee 0)$ . Now, let  $p_N \in \mathcal{P}_N$  be such that  $Q_N(f) = R_I(p_N)$ . Note that for  $q_N, k_N \in \mathcal{P}_N$ , we have

$$\langle R_I^* R_I(q_N), k_N \rangle_{L^2(\partial\mathbb{G})} = \langle R_I(q_N), R_I(k_N) \rangle_{L^2(I)} = \langle \chi_I q_N, k_N \rangle_{L^2(\partial\mathbb{G})} = \langle P_N(\chi_I q_N), k_N \rangle_{L^2(\partial\mathbb{G})},$$

from which it follows that  $R_I^* R_I = T_N^I$ , by definition. Since  $R_I^* Q_N(f) = R_I^* R_I(p_N)$ , we obtain from what precedes that

$$Q_N(f) = R_I(p_N) = R_I (T_N^I)^{-1} P_N(f \vee 0).$$

■

We obtain the following proposition.

**Proposition 3** *Let  $f \in L^2(I)$ ,  $c \in \mathbb{C}$  and  $M > 0$ . The solution  $g_N$  to  $(BEP_N)$  is given by*

$$g_N = (Id - (\gamma_N + 1)T_N^J)^{-1} P_N(f \vee (-\gamma_N c)), \quad (13)$$

where  $\gamma_N \leq 0$ . More precisely,  $\gamma_N$  is equal to 0 if and only if  $Q_N(f) \in \mathcal{B}_{M,c,N|I}$  and if  $Q_N(f) \notin \mathcal{B}_{M,c,N|I}$ , then  $\gamma_N < 0$  and  $g_N$  saturates the constraint:

$$\|g_{N|J} - c\|_{L^2(J)} = M.$$



*Proof:* If  $Q_N(f) \in \mathcal{B}_{M,c,N|_I}$ , then the solution  $g_N$  is such that  $R_I(g_N) = Q_N(f)$  and is the minimum of the function  $p_N \in \mathcal{P}_N \mapsto \|Q_N(f) - p_N|_I\|_{L^2(I)}$ . By Lemma 2, one can have that

$$g_N = (Id - T_N^J)^{-1} P_N(f \vee 0) = (T_N^I)^{-1} P_N(f \vee 0). \quad (14)$$

Suppose now that  $Q_N(f) \notin \mathcal{B}_{M,c,N|_I}$ . Applying [14, Thm 2.1], it follows that there exists a unique solution  $g_N$  to  $(BEP_N)$  given by

$$(R_I^* R_I - \gamma_N R_J^* R_J) g_N = R_I^*(Q_N(f)) - \gamma_N P_N(\chi_J c) = P_N(f \vee (-\gamma_N c)), \quad (15)$$

where  $\gamma_N < 0$  and  $R_J$  is the restriction map from  $\mathcal{P}_N$  onto  $\mathcal{P}_{N|_J}$ . Since we have from the proof of Lemma 2 that  $R_I^* R_I = T_N^I$ , by symmetry, we also have  $R_J^* R_J$  equal to the truncated Toeplitz operator  $T_N^J$ . So, equation (15) can be rewritten in terms of truncated Toeplitz operators as follows

$$(T_N^I - \gamma_N T_N^J) g_N = (Id - (\gamma_N + 1) T_N^J) g_N = P_N(f \vee (-\gamma_N c)),$$

where  $\gamma_N < 0$  is such that  $\|g_N|_J - c\|_{L^2(J)} = M$ . The solution  $g_N$  of  $(BEP_N)$  is given by (13). Note that if  $\gamma_N = 0$ , we find again equation (14). ■

Observe that a similar result holds for truncated versions of Problem 2, with  $c = c_N = 1/|J| \int_J g_N|_J$  in equation (8), see section 3.2.1.

**Remark 3** We define the functions  $m_N$  ( $N \in \mathbb{N}$ ) and  $m : (-\infty, 0] \rightarrow [0, +\infty)$  as follows:

$$\begin{aligned} m_N(t) &= \|(Id - (t+1)T_N^J)^{-1} P_N(f \vee 0)|_J - c\|_{L^2(J)}, \\ m(t) &= \|(Id - (t+1)T^J)^{-1} P_{H^2}(f \vee 0)|_J - c\|_{L^2(J)}. \end{aligned} \quad (16)$$

Then the saturation of the constraint in the bounded extremal problems (1), (2) and  $(BEP_N)$  implies that

$$m_N(\gamma_N) = m(\gamma) = M. \quad (17)$$

Note that the operators  $R_I$  and  $R_J$  have the same role as  $A$  and  $B$  appearing in section 3. Likewise, we have that, for  $\Omega = I$  or  $J$ ,

$$\begin{aligned} R_I^* : \mathcal{P}_{N|_\Omega} &\longrightarrow \mathcal{P}_N \\ p_N|_\Omega &\longmapsto P_N(p_N|_\Omega \vee 0) = P_N(\chi_\Omega p_N). \end{aligned}$$

Observe further that  $T_N^\Omega = P_N T_{|\mathcal{P}_N}^\Omega$  while for  $g \in H^2(\mathbb{G})$ ,

$$P_N T^\Omega g = T_N^\Omega P_N g + P_N T^\Omega (g - P_N g) = T_N^\Omega P_N g + P_N [(P_N \chi_\Omega) R_{N_\infty} g],$$

if we let  $R_{N_\infty} = Id - P_N$  on  $H^2(\mathbb{G})$  (see also section 5.2 for  $\mathbb{G} = \mathbb{A}$ ).

The finite dimensional truncated problem  $(BEP_N)$  could also be approached and solved using arguments from convex optimization (cf. [16]).

## 5 Solution to $(BEP_N)$ in the annulus

Now, we assume that  $\mathbb{G}$  is the annulus  $\mathbb{A}$  defined by  $\mathbb{D} \setminus s\overline{\mathbb{D}}$  with boundary  $\partial\mathbb{A} = \mathbb{T} \cup s\mathbb{T}$ . We also suppose that  $I$  is equal to the unit circle  $\mathbb{T}$  and  $J$  to  $s\mathbb{T}$ .

### 5.1 Explicit expressions in the annulus

We construct the solution  $g_N$  to  $(BEP_N)$  with  $c = 0$ , for this particular configuration, for which explicit expressions of  $P_N$ ,  $T_N^{s\mathbb{T}}$  and  $g_N$  will be obtained.

We recall the following characterization from [29] of functions in  $H^2(\mathbb{A})|_{\partial\mathbb{A}}$ .

**Theorem 3** *Let  $x \in L^2(\partial\mathbb{A})$  such that*

$$x|_{\mathbb{T}}(e^{i\theta}) = \sum_{k \in \mathbb{Z}} a_k e^{ik\theta} \quad \text{and} \quad x|_{s\mathbb{T}}(se^{i\theta}) = \sum_{k \in \mathbb{Z}} b_k s^k e^{ik\theta},$$

*almost everywhere on  $\mathbb{T}$  and  $s\mathbb{T}$  respectively. Then,  $x \in H^2(\mathbb{A})|_{\partial\mathbb{A}}$  if and only if  $b_k = a_k$ .*

**Remark 4** *If  $x \in H^2(\mathbb{A})|_{\partial\mathbb{A}}$ , then by Theorem 3, we have that  $a_k = b_k$ ,*

$$P_N x(z) = \sum_{k=-N}^N a_k z^k,$$

*and  $P_N x$  is the truncation at order  $N$  of the Laurent expansion of  $x$ .*

The next lemma computes the orthogonal projection  $P_N$  from  $L^2(\partial\mathbb{A})$  onto  $\mathcal{P}_N$ .

**Lemma 3** *Let  $x \in L^2(\partial\mathbb{A})$  with Fourier series on  $\mathbb{T}$  and on  $s\mathbb{T}$  given by*

$$x|_{\mathbb{T}}(e^{i\theta}) = \sum_{k \in \mathbb{Z}} a_k e^{ik\theta} \quad \text{and} \quad x|_{s\mathbb{T}}(se^{i\theta}) = \sum_{k \in \mathbb{Z}} b_k s^k e^{ik\theta},$$

*almost everywhere on  $\mathbb{T}$  and  $s\mathbb{T}$  respectively. Then, for  $z \in \mathbb{A}$ ,*

$$P_N x(z) = \sum_{k=-N}^N \frac{a_k + s^{2k} b_k}{1 + s^{2k}} z^k. \quad (18)$$

*Proof:* We have that  $P_N$  is the truncation at order  $N$  of the Laurent expansion of the projection onto  $H^2(\mathbb{A})$  of  $x$ . Indeed, if  $P_{H^2}$  denotes the orthogonal projection from  $L^2(\partial\mathbb{A})$  onto  $H^2(\mathbb{A})$ , then  $P_N x = P_N(P_{H^2} x)$  since  $(x - P_{H^2} x) \in (H^2(\mathbb{A}))^\perp \subset \mathcal{P}_N^\perp$ . By [34, Lem. 4.1], we have for  $z \in \mathbb{A}$  the Laurent expansion:

$$P_{H^2} x(z) = \sum_{k \in \mathbb{Z}} \frac{a_k + s^{2k} b_k}{1 + s^{2k}} z^k, \quad \text{for } z \in \mathbb{A},$$

whose truncation at order  $N$  is then given by (18), see Remark 4. ■

The next proposition gives an explicit expression of the solution  $g_N$  to  $(BEP_N)$ .

**Proposition 4** *Let  $f \in L^2(\mathbb{T})$  with Fourier series  $\sum_{k \in \mathbb{Z}} a_k e^{ik\theta}$ . Then, for  $z \in \mathbb{A}$ , the solution  $g_N$  to  $(BEP_N)$  in  $\mathbb{A}$  is given by*

$$g_N(z) = \sum_{k=-N}^N \frac{a_k}{1 - \gamma_N s^{2k}} z^k,$$

for a unique  $\gamma_N \leq 0$ . If  $Q_N(f) \notin \mathcal{B}_{M,0,N|_{\mathbb{T}}}$ , then  $\gamma_N < 0$  is such that

$$\sum_{k=-N}^N \frac{|a_k|^2 s^{2k}}{(1 - \gamma_N s^{2k})^2} = M^2.$$

*Proof:* Every  $p_N \in \mathcal{P}_N$  can be written for  $z \in \mathbb{A}$  as

$$p_N(z) = \sum_{k=-N}^N a_k z^k.$$

Then,

$$T_N^{\mathbb{T}} p_N(z) = \sum_{k=-N}^N \frac{a_k}{1 + s^{2k}} z^k \quad \text{and} \quad T_N^{s\mathbb{T}} p_N(z) = \sum_{k=-N}^N \frac{a_k s^{2k}}{1 + s^{2k}} z^k.$$

Indeed, since  $(\chi_{\mathbb{T}} p_N)|_{\mathbb{T}}(e^{i\theta}) = \sum_{k=-N}^N a_k e^{ik\theta}$  and  $(\chi_{\mathbb{T}} p_N)|_{s\mathbb{T}}(se^{i\theta}) = 0$  almost everywhere on  $\mathbb{T}$  and  $s\mathbb{T}$  respectively, the result follows from Lemma 3. Similar arguments hold for the expression of  $T_N^{s\mathbb{T}}$ . Proposition 3 and expression (13) of the solution to  $(BEP_N)$  leads to the conclusion.  $\blacksquare$

**Remark 5** The orthonormal basis  $(e_k)_{-N \leq k \leq N}$  of  $\mathcal{P}_N$  where  $e_k(z) = z^k(1 + s^{2k})^{-1/2}$  for  $z \in \mathbb{A}$  is a basis of eigenvectors of  $T_N^{\mathbb{T}}$  and  $T_N^{s\mathbb{T}}$ . Moreover, the matrix of  $T_N^{\mathbb{T}}$  and  $T_N^{s\mathbb{T}}$  respectively in the basis  $(e_k)_{-N \leq k \leq N}$  are diagonal and so, if  $q_N$  is given by  $q_N(z) = \sum_{k=-N}^N b_k z^k$ , then

$$(T_N^{\mathbb{T}})^{-1} q_N(z) = \sum_{k=-N}^N b_k (1 + s^{2k}) z^k \quad \text{and} \quad (T_N^{s\mathbb{T}})^{-1} q_N(z) = \sum_{k=-N}^N b_k \frac{(1 + s^{2k})}{s^{2k}} z^k, \quad z \in \mathbb{A}.$$

Likewise, if the Fourier series of  $f \in L^2(\mathbb{T})$  is given by  $\sum_{k \in \mathbb{Z}} a_k e^{ik\theta}$ , then we have that for all  $N \in \mathbb{N}$ ,

$$Q_N(f)(e^{i\theta}) = \sum_{k=-N}^N a_k e^{ik\theta}, \quad \text{for almost every } e^{i\theta} \in \mathbb{T}.$$

Further, whenever  $f \in H^2(\mathbb{A})|_{\partial\mathbb{A}}$ , it holds from Remark 4 that  $Q_N(f|_{\mathbb{T}}) = (P_N f)|_{\mathbb{T}}$ .

We will denote by  $\mathcal{C}_M^2$  the set  $\{h \in H^2(\mathbb{A}), \|h|_{s\mathbb{T}}\|_{L^2(s\mathbb{T})} \leq M\}$  (which coincides with the approximation class  $\mathcal{B}_{M,0}$  for  $p = 2$ , see Section 3).

**Lemma 4** If  $f \in L^2(\mathbb{T})$  but  $f \notin \mathcal{C}_{M|_{\mathbb{T}}}^2$ , there exists  $N_0 \in \mathbb{N}$  such that for  $N \geq N_0$ ,  $Q_N f \notin \mathcal{B}_{M,0,N|_{\mathbb{T}}}$ , while for  $N < N_0$ ,  $Q_N f \in \mathcal{B}_{M,0,N|_{\mathbb{T}}} \subset \mathcal{B}_{M,0,N_0-1|_{\mathbb{T}}}$ .

*Proof:* Assume  $f \notin \mathcal{C}_{M|_{\mathbb{T}}}^2$ . In any cases  $Q_N f \in \mathcal{P}_{N|_{\mathbb{T}}} \subset H^2(\mathbb{A})|_{\mathbb{T}}$  is such that  $\|f - Q_N(f)\|_{L^2(\mathbb{T})} \rightarrow 0$  as  $N \rightarrow +\infty$ . Let  $p_N \in \mathcal{P}_N$ ,  $p_N|_{\mathbb{T}} = Q_N(f)$ .

• Suppose first that  $f \notin H^2(\mathbb{A})|_{\mathbb{T}}$ ; then it follows as a consequence of the density result in Proposition 1 in that particular setting, see also [13, Prop. 4.1], that  $\|p_N\|_{L^2(s\mathbb{T})} \rightarrow \infty$  as  $N \rightarrow \infty$ , whence there exist  $N_0$  such that  $\|p_{N_0}\|_{L^2(s\mathbb{T})} > M$ .

• Suppose now that  $f \in H^2(\mathbb{A})|_{\mathbb{T}}$ , and  $f = F|_{\mathbb{T}}$  for  $F \in H^2(\mathbb{A})$  with  $\|F\|_{L^2(s\mathbb{T})} > M$ . In this case,  $Q_N(f) = (P_N F)|_{\mathbb{T}} = p_N|_{\mathbb{T}}$  (see Remark 5), and because  $\|F - p_N\|_{L^2(s\mathbb{T})} \rightarrow 0$ , there exists

$N_0$  such that  $\|p_{N_0}\|_{L^2(s\mathbb{T})} > M$ .

In both cases, one can choose  $N_0$  to be the smallest such integer. In particular, if  $p_N$  has Fourier coefficients  $(a_k)$ ,  $k = -N, \dots, N$ , the quantity  $\|p_n\|_{L^2(s\mathbb{T})}^2 = \sum_{k=-n}^n |a_k|^2 s^{2k}$  is increasing with  $n$  for  $0 \leq n \leq N$ , and we get the conclusion. We also get that necessarily  $a_{n_0} \neq 0$  for some  $n_0 \in \mathbb{Z}$  with  $|n_0| = N_0 \leq N$ . ■

## 5.2 Error estimates

Now, we are interested in establishing some error estimates between the solution  $g$  to Problem (1) and  $g_N$  to  $(BEP_N)$  with  $c = 0$  for the same given constraint  $M > 0$ . In the sequel, we will mention the dependence of  $g$  and  $g_N$  on the Lagrange parameters  $\gamma$  and  $\gamma_N$  respectively, that also depend on the constraint  $M$ . Let  $R_{N\infty}(\sum_{k \in \mathbb{Z}} a_k e^{ik\theta})(z) = \sum_{|k| > N} a_k z^k$ , on  $L^2(\mathbb{T})$ .

**Proposition 5** *Let  $f \in L^2(\mathbb{T})$  with Fourier series  $\sum_{k \in \mathbb{Z}} a_k e^{ik\theta}$  and  $f \notin \mathcal{C}_{M|\mathbb{T}}^2$ . Then, the sequence of parameters  $(\gamma_N)_{N \in \mathbb{N}}$  is non-increasing and converges to  $\gamma$  and there exists  $N_0 \in \mathbb{N}$  such that for all  $N \geq N_0$ , we have that, for some constant  $C_0 > 0$ ,*

$$0 \leq \gamma_N - \gamma \leq C_0 s^{2N} \|R_{N\infty}(f)\|_{L^2(\mathbb{T})}^2. \quad (19)$$

We may take  $C_0 = \max(1, 1/\gamma^2) (s^{-n_0} - \gamma s^{n_0})^4 / 2 |a_{n_0}|^2$ , for some  $n_0 \in \mathbb{Z}$  with  $|n_0| = N_0$  such that  $a_{n_0} \neq 0$  (or simply, if  $a_0 \neq 0$ ,  $C_0 = \max(1, 1/\gamma^2) (1 - \gamma)^4 / 2 |a_0|^2$ ).

*Proof:* Let  $f \notin \mathcal{C}_{M|\mathbb{T}}^2$ . From [2, 14], and the results recalled in section 4.1, we know that  $\gamma \neq 0$  and Lemma 4 together with Proposition 3 imply the existence of  $N_0 \in \mathbb{N}$  such that for all  $N \geq N_0$ ,  $\gamma_N < 0$ . Let  $N \geq N_0$ . From (16) together with Proposition 4 and Remark 5, we have for  $t < 0$  that

$$m_N^2(t) = \sum_{k=-N}^N \frac{|a_k|^2 s^{2k}}{(1 - t s^{2k})^2} \quad \text{and} \quad m_{N+1}^2(t) = \sum_{k=-(N+1)}^{N+1} \frac{|a_k|^2 s^{2k}}{(1 - t s^{2k})^2}.$$

The functions  $m_N^2$  and  $m_{N+1}^2$  are continuous and non-increasing, as are their inverse functions. Since Theorem 2 ensures that  $g_N$  saturates the constraint for every  $N \geq N_0$ , (16) implies that

$$\begin{aligned} M^2 = m^2(\gamma) = m_N^2(\gamma_N) &= \sum_{k=-N}^N \frac{|a_k|^2 s^{2k}}{(1 - \gamma_N s^{2k})^2} = m_{N+1}^2(\gamma_{N+1}) \\ &\geq \sum_{k=-N}^N \frac{|a_k|^2 s^{2k}}{(1 - \gamma_{N+1} s^{2k})^2} = m_N^2(\gamma_{N+1}). \end{aligned}$$

Applying the inverse function to  $m_N^2$  to the previous inequality, it follows that  $(\gamma_N)_{N \in \mathbb{N}}$  is non-increasing and in particular,  $\gamma_N = 0$  for  $0 \leq N < N_0$  (see Proposition 3). Now, equality (17) gives that

$$\sum_{k=-N}^N \frac{|a_k|^2 s^{4k} [(1 - \gamma s^{2k})^2 - (1 - \gamma_N s^{2k})^2]}{(1 - \gamma_N s^{2k})^2 (1 - \gamma s^{2k})^2} = \sum_{|k| > N} \frac{|a_k|^2 s^{2k}}{(1 - \gamma s^{2k})^2},$$

which leads to

$$(\gamma_N - \gamma) \sum_{k=-N}^N \frac{|a_k|^2 s^{4k} (2 - (\gamma_N + \gamma) s^{2k})}{(1 - \gamma_N s^{2k})^2 (1 - \gamma s^{2k})^2} = \sum_{|k| > N} \frac{|a_k|^2 s^{2k}}{(1 - \gamma s^{2k})^2}. \quad (20)$$

Since  $\gamma_N, \gamma < 0$ , equality (20) implies that  $\gamma_N > \gamma$ . It follows that

$$\sum_{k=-N}^N \frac{|a_k|^2 s^{4k} (2 - (\gamma_N + \gamma) s^{2k})}{(1 - \gamma_N s^{2k})^2 (1 - \gamma s^{2k})^2} > \sum_{k=-N}^N \frac{2|a_k|^2 s^{4k}}{(1 - \gamma s^{2k})^4} \geq \frac{2|a_{n_0}|^2}{(s^{-n_0} - \gamma s^{n_0})^4}$$

(recall that we choose  $N \geq N_0$  in order to ensure that  $|a_{n_0}| \neq 0$  for  $|n_0| = N_0$ ).

Clearly, we have that

$$\begin{aligned} \sum_{|k| > N} \frac{|a_k|^2 s^{2k}}{(1 - \gamma s^{2k})^2} &= \sum_{k=-\infty}^{-N-1} \frac{|a_k|^2 s^{2k}}{(1 - \gamma s^{2k})^2} + \sum_{k=N+1}^{+\infty} \frac{|a_k|^2 s^{2k}}{(1 - \gamma s^{2k})^2} \\ &\leq \frac{1}{\gamma^2} s^{2N} \sum_{k=-\infty}^{-N-1} |a_k|^2 + s^{2N} \sum_{k=N+1}^{+\infty} |a_k|^2 \leq s^{2N} \max\left(1, \frac{1}{\gamma^2}\right) \|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}^2. \end{aligned}$$

Combining the previous inequalities with equality (20) completes the proof.  $\blacksquare$

In the next Corollary, the index  $N_0$  is the same as the one appearing in Proposition 5, which only depends on  $f$  and  $M$ .

**Corollary 1** *Let  $f \in L^2(\mathbb{T})$  with Fourier series  $\sum_{k \in \mathbb{Z}} a_k e^{ik\theta}$  be such that  $f \notin \mathcal{C}_{M|\mathbb{T}}^2$ . Then, there exist  $C_1, C_2 > 0$  such that for all  $N \geq N_0$ ,*

$$\|g_N - g\|_{L^2(\partial\mathbb{A})} \leq C_1 \|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}^2 + C_2 \|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}.$$

Indeed, we may take  $C_1 = C_0 \|f\|_{L^2(\mathbb{T})}$  and  $C_2 = \max(1, 1/|\gamma|)$ .

In other words,  $\|g_N - g\|_{L^2(\partial\mathbb{A})} = O(\|R_{N_\infty}(f)\|_{L^2(\mathbb{T})})$ , as  $N \rightarrow +\infty$  and the solution  $g_N$  to  $(BEP_N)$  converges in  $L^2(\partial\mathbb{A})$  norm to the solution  $g$  to Problem (1).

*Proof:* By Proposition 4 and [34, Prop. 4.3], we have that

$$\|g_N - g\|_{L^2(\partial\mathbb{A})}^2 = (\gamma_N - \gamma)^2 \sum_{k=-N}^N \frac{s^{4k} (1 + s^{2k}) |a_k|^2}{(1 - \gamma_N s^{2k})^2 (1 - \gamma s^{2k})^2} + \sum_{|k| > N} \frac{|a_k|^2 (1 + s^{2k})}{(1 - \gamma s^{2k})^2}.$$

For  $-N \leq k \leq N$ , we write that

$$\frac{(1 + s^{2k}) s^{4k}}{(1 - \gamma_N s^{2k})^2 (1 - \gamma s^{2k})^2} = \frac{1 + s^{2k}}{(1 - \gamma_N s^{2k})^2 (s^{-2k} - \gamma)^2}.$$

For  $0 \leq k \leq N$ , we have that

$$\frac{1 + s^{2k}}{(1 - \gamma_N s^{2k})^2 (s^{-2k} - \gamma)^2} \leq \frac{2}{(1 - \gamma)^2} \leq \frac{2s^{-4N}}{(1 - \gamma)^2} \leq 2s^{-4N},$$

and for  $-N \leq k \leq -1$ , we have that

$$\frac{1 + s^{2k}}{(1 - \gamma_N s^{2k})^2 (s^{-2k} - \gamma)^2} \leq \frac{1 + s^{-2N}}{s^{2N} - \gamma} \leq 2s^{-4N}.$$

Thus, we obtain that

$$\sum_{k=-N}^N \frac{s^{4k} (1 + s^{2k}) |a_k|^2}{(1 - \gamma_N s^{2k})^2 (1 - \gamma s^{2k})^2} \leq 2s^{-4N} \|f\|_{L^2(\mathbb{T})}^2. \quad (21)$$

Now for  $k > N$ , we have that

$$\frac{1 + s^{2k}}{(1 - \gamma s^{2k})^2} = \frac{1}{(1 - \gamma s^{2k})^2} + \frac{1}{(s^{-k} - \gamma s^k)^2} \leq 1 + s^{2N},$$

and

$$\sum_{k=N+1}^{+\infty} \frac{|a_k|^2 (1 + s^{2k})}{(1 - \gamma s^{2k})^2} \leq (1 + s^{2N}) \sum_{k>N} |a_k|^2.$$

For  $k < -N$ , we have that

$$\frac{1 + s^{2k}}{(1 - \gamma s^{2k})^2} \leq \frac{2}{(s^{-k} - \gamma s^k)^2} \leq \frac{2}{\gamma^2} s^{2N}.$$

As  $s < 1$ , one can write that

$$\sum_{|k|>N} \frac{|a_k|^2 (1 + s^{2k})}{(1 - \gamma s^{2k})^2} \leq 2 \max\left(1, \frac{1}{\gamma^2}\right) \sum_{|k|>N} |a_k|^2.$$

It follows from Proposition 5 that

$$\begin{aligned} \|g_N - g\|_{L^2(\partial\mathbb{A})}^2 &\leq 2C_0^2 \|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}^4 \times \|f\|_{L^2(\mathbb{T})}^2 + 2 \max\left(1, \frac{1}{\gamma^2}\right) \|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}^2 \\ &\leq 2C_1^2 \|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}^4 + 2C_2^2 \|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}^2, \end{aligned}$$

with  $C_1 = C_0 \|f\|_{L^2(\mathbb{T})}$  and  $C_2 = \max(1, 1/|\gamma|)$ . ■

Further, one directly deduces from (21) and Proposition 5 that as  $N \rightarrow \infty$ :

$$\|g_N - P_N g\|_{L^2(\partial\mathbb{A})} \leq \sqrt{2} C_0 \|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}^2 \times \|f\|_{L^2(\mathbb{T})} = O\left(\|R_{N_\infty}(f)\|_{L^2(\mathbb{T})}^2\right).$$

## 6 Numerical illustrations

In order to illustrate the considerations and results of Sections 4, 5 for  $\mathbb{G} = \mathbb{A}$  and  $I = \mathbb{T}$ , we let  $f = f_\varepsilon \in L^2(\mathbb{T}) \setminus H^2(\mathbb{A})|_{\mathbb{T}}$  be explicitly defined as a perturbation of some function  $f_0 \in H^2(\mathbb{A})$ :

$$f(e^{i\theta}) = f_{0|\mathbb{T}}(e^{i\theta}) + \frac{\varepsilon/d}{e^{i\theta} - d},$$

for some (small)  $\varepsilon > 0$ ,  $d \in \mathbb{A}$ , and

$$f_0(z) = \frac{1}{z-a} + \frac{1}{z-b} \in H^2(\mathbb{A}), \text{ with } a \in s\mathbb{D}, b \in \mathbb{C} \setminus \overline{\mathbb{D}}.$$

For  $N \in \mathbb{N}$ ,  $N \geq 1$ , we then have:

$$Q_N f = f_{N|_{\mathbb{T}}}, \text{ with } f_N(z) = f_{0,N}(z) + \varepsilon \sum_{p=-1}^{-N} \frac{z^p}{d^{p+2}} \in \mathcal{P}_N,$$

$$\text{and } f_{0,N}(z) = P_N f_0(z) = - \sum_{p=0}^N \frac{z^p}{b^{p+1}} + \sum_{p=-1}^{-N} \frac{z^p}{a^{p+1}}, \text{ while } Q_N(f_{0|_{\mathbb{T}}}) = f_{0,N|_{\mathbb{T}}} = (P_N f_0)|_{\mathbb{T}}.$$

We fix  $s = 1/3$  and the annulus  $\mathbb{A}$ , and take  $a = 1/5$ ,  $b = 5/3$ ,  $d = 11/30$  which determine  $f_0$  and  $f$ . All the computations and illustrations are made with *Maple 15*.

Because  $\|f_{0|_{s\mathbb{T}}}\|_{L^2(s\mathbb{T})} \simeq 3.8$ , we choose  $M_r = 4$  as a reference value for the constraint  $M$ , so that  $f_0 \in \mathcal{B}_{M_r,0}$ . We thus expect the solution  $g_N$  to  $(BEP_N)$  to also provide a reasonable approximation to the  $H^2(\mathbb{A})$ -function  $f_0$  (not only to  $f$ ), for large enough  $N$ . Indeed, the choice  $M = M_r$ , together with the saturation of the constraint by  $g_N$  if  $f_N \notin \mathcal{B}_{M_r,0,N}$ , will ensure that  $M_r = \|g_{N|_{s\mathbb{T}}}\|_{L^2(s\mathbb{T})} > \|f_{0|_{s\mathbb{T}}}\|_{L^2(s\mathbb{T})}$ , whence

$$\|f_{0,N|_{\mathbb{T}}} - g_{N|_{\mathbb{T}}}\|_{L^2(\mathbb{T})} \leq \|f_{0,N|_{\mathbb{T}}} - f_{N|_{\mathbb{T}}}\|_{L^2(\mathbb{T})} + \|f_{N|_{\mathbb{T}}} - g_{N|_{\mathbb{T}}}\|_{L^2(\mathbb{T})} \leq 2 \|f_{0,N|_{\mathbb{T}}} - f_{N|_{\mathbb{T}}}\|_{L^2(\mathbb{T})},$$

because  $f_{0,N} \in \mathcal{B}_{M_r,0,N}$ .

Table 1 relates different values of  $\varepsilon$  and  $M$  to the corresponding integer  $N_0 = N_0(M, \varepsilon)$  for which  $f_{N_0} \notin \mathcal{B}_{M,0,N_0}$  and  $f_{N_0-1} \in \mathcal{B}_{M,0,N_0-1}$ , see Lemma 4.

We next compute the solutions  $g_N$  to  $(BEP_N)$  associated to  $f$ ,  $c = 0$ , and a number of values of  $\varepsilon$ ,  $N$ , and  $M$ .

In Figure 1, we took  $M = M_r = 4$ . The left-hand plot corresponds to the pointwise error  $|(f_{N|_{\mathbb{T}}} - g_{N|_{\mathbb{T}}})(e^{i\theta})|$ ,  $e^{i\theta} \in \mathbb{T}$ , for  $N = 10$  and some values of  $\varepsilon$  between  $10^{-1}$  and  $10^{-2}$ . The right-hand plot shows the same quantity, for  $\varepsilon = 5 \cdot 10^{-2}$  and some values of  $N$  between 3 and 50. Figure 1 shows that  $\varepsilon = 5 \cdot 10^{-2}$  and  $N = 10$  ensure a small enough pointwise approximation error, and still permit  $f_N$  and  $f_{0,N}$  to be numerically distinct on  $\mathbb{T}$ ; see also Figure 2, left.

Numerical computations of the quadratic error (the criterion) with  $M = M_r$  give that:

- for  $N = 10$ ,  $\|f_{N|_{\mathbb{T}}} - g_{N|_{\mathbb{T}}}\|_{L^2(\mathbb{T})} \leq .18$  and has the expected increasing behaviour with  $\varepsilon \in [10^{-2}, 10^{-1}]$ ; further,  $\|f - f_{0,N|_{\mathbb{T}}}\|_{L^2(\mathbb{T})} = C \varepsilon$ , with  $C \simeq 2.9$  (in accordance with the value of the parameter  $d$ );
- for  $\varepsilon = 5 \cdot 10^{-2}$ ,  $\|f_{N|_{\mathbb{T}}} - g_{N|_{\mathbb{T}}}\|_{L^2(\mathbb{T})}$  is contained within  $(.05, .08)$  when  $N = 3, \dots, 50$ .

We now fix  $N = 10$ ,  $\varepsilon = 5 \cdot 10^{-2}$ , whence  $f_N \notin \mathcal{B}_{M,0,N}$  for  $M \leq M_r$  and the other values of  $M$  considered in Figures 2, 3, see Table 1 to the effect that  $N > N_0$ .

Figures 2, 3 show Nyquist plots (real and imaginary parts) of the functions  $f_N$ ,  $f_{N,0}$  and  $g_N$  on  $\mathbb{T}$ , for different values of  $M$ . In Figure 2, the fact that the error between  $f_{N|_{\mathbb{T}}}$  and  $g_{N|_{\mathbb{T}}}$

	$\varepsilon =$	$10^{-2}$	$2.10^{-2}$	$3.10^{-2}$	$5.10^{-2}$	$6.10^{-2}$	$10^{-1}$
$M = 4.5$	$N_0 =$	26	17	10	4	3	2
$M = M_r = 4$	$N_0 =$	10	4	3	2	2	2
$M = 3.81$	$N_0 =$	3	3	2	2	2	1
$M = 3.5$	$N_0 =$	2	2	2	2	1	1

Table 1: Smallest  $N_0 = N_0(M, \varepsilon) \in \mathbb{N}$  such that  $f_{N_0} \notin \mathcal{B}_{M,0,N_0}$ , for different values of  $M$  and of  $\varepsilon \in [10^{-2}, 10^{-1}]$ .

decreases with  $M$  corresponds to the fact that on the right-hand plot, for  $M = 4.5$ , the two functions are not distinct. For smaller values of  $M$ , in Figures 3,  $g_{N|_{\mathbb{T}}}$  becomes closer to  $f_{0,N|_{\mathbb{T}}}$ .

The influence of  $\varepsilon$  and of the parameters  $a, b, d$  remain to be numerically studied, together with more sophisticated functions (or data) on  $\mathbb{T}$ .

## 7 Conclusion

### 7.1 Slepian functions

Questions concerning the computation of the solutions to  $(BEP_N)$  are naturally connected to the existence of a basis of functions in  $\mathcal{P}_N$  which concentrate their energy over  $I$ . Indeed, one can seek a basis of functions in  $L^2(\partial\mathbb{G})$  mostly concentrated on  $I$ : these functions, when they exist, are called Slepian functions, following a series of articles by D. Slepian, among which we mention [32] for  $\mathbb{G} = \mathbb{D}$ .

In this context, already related to applications in signal processing or 2D inverse recovery problems, a criterion to compute Slepian functions (see [32, 33]) consists in maximizing the ratio

$$\frac{\|g|_I\|_{L^2(I)}}{\|g|_{\partial\mathbb{G}}\|_{L^2(\partial\mathbb{G})}},$$

among the (finite-dimensional) space of “band-limited” functions (polynomials  $g \in \mathcal{P}_N$ , with fixed  $N$ , in this discrete situation). A family of such functions coincide with the eigenfunctions of the truncated Toeplitz operator  $T_N^I$ . One of their most interesting features here would be that they form an orthogonal basis of functions both on  $\mathcal{P}_{N|_{\partial\mathbb{G}}}$  (in  $L^2(\partial\mathbb{G})$ ) and on  $\mathcal{P}_{N|_I}$  (in  $L^2(I)$ ). Note that in the annular setting of  $H^2(\mathbb{A})$  ( $\mathbb{G} = \mathbb{A}$ ) and for the diagonal situation where  $I = \mathbb{T} \subset \partial\mathbb{A}$  coincides with one of the two connected components of  $\partial\mathbb{A}$ , the Fourier basis provides an example of such Slepian functions in infinite dimension.

More generally, such functions have also been studied [24, 31, 33] when:

- $\mathbb{G}$  is the unit ball in  $\mathbb{R}^3$  with  $I$  a polar cap contained in  $\partial\mathbb{G} = \mathbb{S}$ , and the Slepian functions are sought among spherical polynomials of prescribed degree  $N$  (spherical harmonic basis); their computation however is not so easy for large  $N$  and requires additional considerations, some of which are developed in [24, 31].
- $\mathbb{G}$  is a half-plane and  $I$  an interval of  $\partial\mathbb{G} = \mathbb{R}$ , the minimization class being a set of functions  $f \in L^2(\partial\mathbb{G})$  whose Fourier transforms are compactly supported, with a prescribed support (the “bandwidth”), while the Slepian functions are the so-called prolate spheroidal wave functions), see [33].



## 7.2 Model spaces

Following Remark 2, the space  $\mathcal{P}_N$  can be decomposed as follows for  $\mathbb{G} = \mathbb{A}$  and  $p = 2$ :

$$\mathcal{P}_N = \text{span} \{z^k, -N \leq k \leq N\} = \text{span} \{z^k, 0 \leq k \leq N\} \oplus \text{span} \{z^k, -N \leq k \leq -1\}$$

and so  $\mathcal{P}_N$  can be seen as the orthogonal sum  $K_\Theta \oplus K_{\tilde{\Theta}}$  where  $K_\Theta$  is the model space of  $H^2(\mathbb{D})$  associated with the Blaschke product  $\Theta(z) = z^{N+1}$  (see [25, Part B, Ch. 3]) and

$$K_{\tilde{\Theta}} = H_0^2(\mathbb{C} \setminus s\mathbb{D}) \cap \left( \tilde{\Theta} H_0^2(\mathbb{C} \setminus s\mathbb{D}) \right)^\perp = H_0^2(\mathbb{C} \setminus s\mathbb{D}) \cap \tilde{\Theta} H^2(s\mathbb{D})$$

is the model space of  $H_0^2(\mathbb{C} \setminus s\mathbb{D})$  associated with  $\tilde{\Theta}(z) = z^{-N}$ . The special (simple) form of  $\Theta$  above leads to an orthogonal decomposition in  $L^2(\partial\mathbb{A})$  (the second  $\oplus$ ):

$$H^2(\mathbb{A}) = (K_\Theta \oplus K_{\tilde{\Theta}}) \oplus (\Theta H^2(\mathbb{D}) \oplus \tilde{\Theta} H_0^2(\mathbb{C} \setminus s\mathbb{D})),$$

whereas this need not hold for more general inner functions  $\Theta$  (even for Blaschke products). One may also consider other model spaces, determined by infinite Blaschke products or more general inner functions  $\Theta$ , for  $1 < p < \infty$  as well.

## 7.3 Other related issues

One can give integral representations of  $P_N(h)$  for  $h \in L^2(\partial\mathbb{G})$ . First, when  $h \in L^2(\mathbb{T})$ , we have that  $P_N(h) \in \mathcal{P}_N$  where  $\mathcal{P}_N$  is the model space  $K_\Theta$ , with  $\Theta(z) = z^{N+1}$  (see section 7.2). Since the reproducing kernel of  $\mathcal{P}_N$  is given by

$$K_z^N(\omega) = \frac{1 - \bar{z}^{N+1}\omega^{N+1}}{1 - \bar{z}\omega}, \quad z, \omega \in \mathbb{D},$$

it follows that for  $z \in \mathbb{D}$ ,

$$\begin{aligned} P_N(h)(z) &= \langle P_N(h), K_z^N \rangle_{L^2(\mathbb{T})} = \langle h, K_z^N \rangle_{L^2(\mathbb{T})} \\ &= \frac{1}{2i\pi} \int_{\mathbb{T}} h(\zeta) \frac{1 - z^{N+1}\bar{\zeta}^{N+1}}{1 - z\bar{\zeta}} d\zeta. \end{aligned}$$

When  $\mathbb{G} = \mathbb{A}$ , we recall that the reproducing kernel of  $H^2(\mathbb{A})$  is given by

$$K_z(\omega) = \sum_{k=-\infty}^{+\infty} \frac{\bar{z}^k \omega^k}{1 + s^{2k}}, \quad z, \omega \in \mathbb{A},$$

(see [1] for example) and  $P_N(K_z) = \sum_{k=-N}^N \frac{\bar{z}^k \omega^k}{1 + s^{2k}}$  (see remark 4). Now, if  $h \in L^2(\partial\mathbb{A})$ , we have for  $z \in \mathbb{A}$  that

$$\begin{aligned} P_N(h)(z) &= \sum_{k=-N}^N \frac{\hat{h}_{|\mathbb{T}}(k) + \hat{h}_{|s\mathbb{T}}(k) s^k}{1 + s^{2k}} z^k \\ &= \sum_{k=-N}^N \frac{z^k}{1 + s^{2k}} \left[ \frac{1}{2i\pi} \int_{\mathbb{T}} h_{|\mathbb{T}}(\zeta) \bar{\zeta}^{k+1} d\zeta + \frac{s^k}{2i\pi} \int_{\mathbb{T}} h_{|s\mathbb{T}}(s\zeta) \bar{\zeta}^{k+1} d\zeta \right] \\ &= \frac{1}{2i\pi} \int_{\mathbb{T}} h_{|\mathbb{T}}(\zeta) \overline{P_N(K_z)(\zeta)} d\zeta + \frac{1}{2i\pi s} \int_{s\mathbb{T}} h_{|s\mathbb{T}}(\zeta) \overline{P_N(K_z)(\zeta)} d\zeta. \end{aligned}$$

In the Hardy spaces  $H^2(\mathbb{G})$  and the model spaces (polynomials)  $\mathcal{P}_N$ , reproducing kernels allow one to get integral representations of the projections  $P_{H^2}$  and  $P_N$ , whence of the solutions  $g$  and  $g_N$  to the bounded extremal problems, from the available boundary data. Such Carleman integral formulas are established in [7] for  $\mathbb{G} = \mathbb{D}$  and  $I \subset \partial\mathbb{G} = \mathbb{T}$ . This is of interest by itself and for further numerics, whose analysis will be undertaken in a subsequent work.

On the same line, the reproducing kernel Hilbert space structure leads to characterizations of traces on  $I \subset \partial\mathbb{G}$  of functions belonging to  $H^2(\mathbb{G})$  with bounded norm, see Section 3.2.2 for related questions, and [3] for  $\mathbb{G} = \mathbb{D}$ . Similar issues could be handled in  $\mathcal{P}_N$  or in other model spaces, with their reproducing kernels.

Let us mention that we did not consider here the cases  $p = 1$  and  $p = \infty$ , where some of the above properties may still be true (the situation  $p = \infty$  in particular is algorithmically tractable and involves Hankel operators, see [8]). One could further consider different constraints on  $J = \partial\mathbb{G} \setminus I$ , such as a  $L^p(J)$ -norm constraint involving the real part of the approximant only, as in [23], or constraints expressed with a different norm.

Another possible extension is to the Hardy classes of gradients of harmonic functions in balls or spherical shells of  $\mathbb{R}^3$ , see [5], with related Toeplitz operators and spherical polynomials. We finally mention [18, 19], where bounded extremal problems in Hardy spaces of pseudo-analytic functions have been studied in  $\mathbb{G} = \mathbb{D}$  and  $\mathbb{A}$ ; this has applications in the analysis of inverse problems in tokamak fusion reactors (plasma boundary recovery) and its discretization should be further studied.

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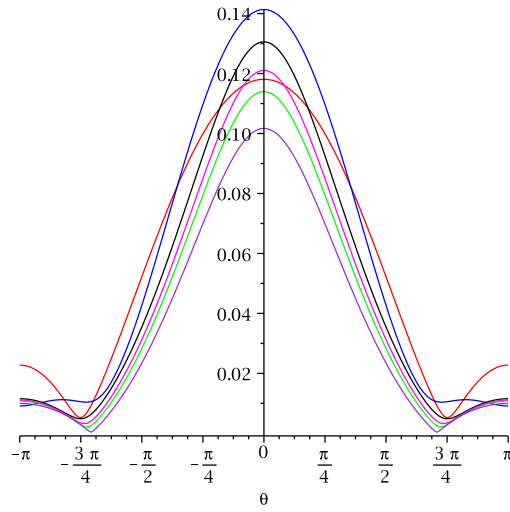
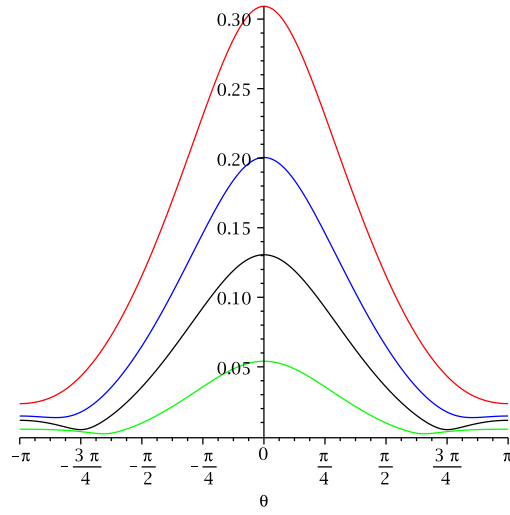


Figure 1:  $|(f_{N|_{\mathbb{T}}} - g_{N|_{\mathbb{T}}})(e^{i\theta})|$ , w.r.t.  $\theta \in [0, 2\pi]$ , with  $M = M_r = 4$ ; top: for  $N = 10$  and  $\varepsilon = 10^{-1}$  (red),  $7 \cdot 10^{-2}$  (blue),  $5 \cdot 10^{-2}$  (black),  $3 \cdot 10^{-2}$  (green); below: for  $\varepsilon = 5 \cdot 10^{-2}$  and  $N = 3$  (red), 4 (blue), 10 (black), 20 (green), 30 (pink), 50 (violet).

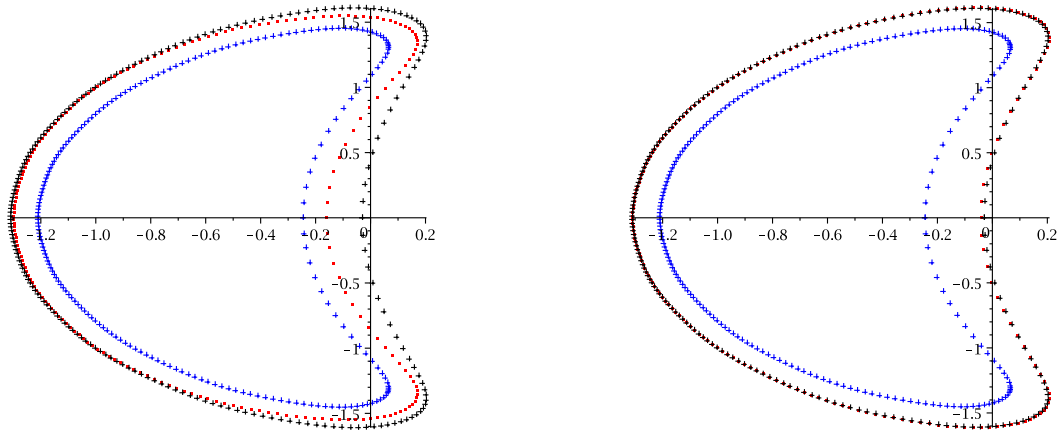


Figure 2:  $f_{N|_{\mathbb{T}}}$  (black crosses),  $f_{0,N|_{\mathbb{T}}}$  (blue crosses) and  $g_{N|_{\mathbb{T}}}$  (red dots) for  $N = 10$ ,  $\varepsilon = 5.10^{-2}$ ; left:  $M = M_r = 4$ , right:  $M = 4.5$ .

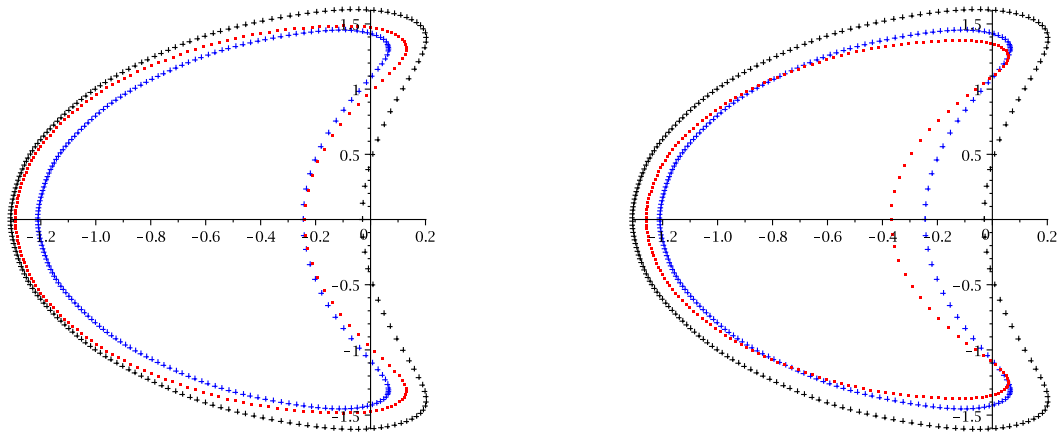


Figure 3:  $f_{N|_{\mathbb{T}}}$  (black crosses),  $f_{0,N|_{\mathbb{T}}}$  (blue crosses) and  $g_{N|_{\mathbb{T}}}$  (red dots) for  $N = 10$ ,  $\varepsilon = 5.10^{-2}$ ; left:  $M = 3.81$ ; right:  $M = 3.5$ .



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